Contract No. F61775-99-WE088
SPC 99-4088

EXPERIMENTAL RESEARCH ON OPTIMIZATION OF NEUTRON YIELD FROM PF-360 MACHINE

Item 0004

Final report on accomplishing the work
outlined in the contract description

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Otwock-Swierk, August 2000

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1. Introduction

According to the SPC 99-4088 proposal the main objective of the F61775-99-WE088 contract was to investigate new techniques in order to overcome the neutron saturation effect and to increase the maximum neutron yield [1]. It was proposed that to achieve this objective the PF-360 machine operated at IPJ-Swierk should be modified and additional measuring equipment for neutron studies should be installed. After that detailed neutron measurements should be performed under selected experimental conditions, and in particular for the optimization of neutron yields – there should be applied special cryogenic targets of gas-puffed targets with appropriate modifications of the electrode-insulator configuration.

Numerous Plasma-Focus (PF) experiments, which were performed at different laboratories all over world, showed a promising sealing of the neutron yield from D-D fusion reactions (Y_n) described by a simple formula $Y_n \sim W_o^a$, where W_o means the input energy, and a =2.0-2.2 depending on a machine type and input energy value [2]. Considering PF physics more grounded is the scaling formula $Y_n \sim I_m^ß$, where I_m means the maximum discharge current and ß = 3.3 – 4.4 depending also on the experiment scale [2]. Some investigations extended this scaling to a multi-MJ (and multi-MA) level [3], but this hypothesis has not been supported by experimental studies so far. Experimentally it was found that the neutron emission saturates or even decreases when the initial energy input and discharge current are increased above certain threshold values [2, 4]. Hence, the record neutron yields from the largest PF machines operated at W_o < 800 kJ, reached about 10^{12} neutrons/shot only.

Intense short lasting pulses of fast neutrons could be applied for different purposes, ranging from basic nuclear studies (e.g. the production of short living isotopes) to application-oriented research (e.g. the fast neutron radiography). Therefore, many research teams have tried to optimize PF machines in order to increase the neutron yield. Numerous tests of various electrodes and insulators showed the most promising electrode-configurations [4]. Also the application of appropriate materials (e.g. special ceramic insulators) made possible to operate PF facilities at higher energy (and yield) levels [5].

All activities connected with this project and the most important results of experimental tests were described in two interim reports [6-7]. This final report presents a short summary of all the successive phases of the contract realization,

with particular attention paid to the neutron optimization measurements. It also contains some final conclusions and new proposals.

2. Preliminary phase of the contract

During the early experimental studies performed with the old PF-360 machine, which was equipped with Mather-type electrodes of 100 mm and 150 mm in diameter, 300 mm in length, the maximum neutron yield from discharges carried out at 171 kJ, 36 kV, was about 1.2 x 10^{11} neutrons/shot [8]. Different techniques, involving changes in the electrode-insulator configuration, the application of the pre-ionization etc., were applied in order to improve the neutron yield. Also extensive studies of PF dynamics and temporal correlation of X-rays, fast electrons, energetic ions, and fusion products, have been continued for several years [9], but the neutron saturation effect has not been overcome.

Taking into consideration results of the “snow-plough” modeling and the previous experimental studies, for the realization of the contract in question it was decided to apply larger coaxial electrodes of 120 mm and 170 mm in diameter, respectively. Both electrodes were made 300 mm in length, but the inner electrode was embraced with a ceramic insulator of 80 mm in length. It was also decided to perform a detailed technical inspection and appropriate modernization of the PF-360 current pulse generator, and in particular to replace all eroded spark-gaps, as well as old charging resistors and current limiting varistors.

In order to increase the neutron yield it was proposed to make use of fast deuterons, which escape from the PF region. For this purpose there was designed an additional cryogenic target, which consisted of a metal plate cooled down by an inner flow of liquid nitrogen, and was covered with a thin layer of the “heavy-ice” formed of the “heavy-water” (D_2O) vapor. Such a planar cryogenic target, bombarded by fast deuterons, should produce additional fusion-originated neutrons.

Another technique, as proposed under the contract, was based on the application of an additional deuterium-gas target produced within the PF region. Basing on our experience gained during joint German-Polish experiments in Stuttgart [10], it was decided to design a special fast-acting gas valve to be installed inside the inner electrode. It was planned to operate that value well in advance of the main

discharge triggering, to make possible an interaction of the collapsing current sheath (CS) layer with the deuterium-gas target in order to increase the fusion neutron yield.

3. The first phase of the contract

During the first phase of the reported contract the PF-360 machine was carefully inspected. There were installed new optical windows and new measuring tools. A general view of the PF-360 experimental chamber after modernization has been shown in Fig. 1.

To make possible time-integrated measurements of fusion-produced neutrons there were installed silver activation counters placed in the plane of the electrode ends, but at different radial- and angular-positions (d_1 = 103 cm $\Theta_1 = 0^0$; d_2 = 352 cm, $\Theta_2 = 74.7^0$). In order to enable time-resolved measurement of hard X-ray and fast neutron pulses, there were used two scintillator-photomultiplier sets, which were placed side-on the electrode ends, at different positions (at $\Theta_1 = 79.1^0$, d_1 = 262 cm, and at $\Theta_2 = 44.1^0$, d_2 = 383 cm, respectively).

The PF-360 current pulse generator was modified, and in particular the charging water-resistors were replaced by the solid ones. Also the current-limiting SiC-plates were replaced by modern metal-oxide varistors. Exploitation tests of individual condenser subsections showed that at the 20 kV charging voltage each unit can supply about 180 kA, and the whole modernized PF-360 generator can deliver about 3 MA current pulse.

During the first phase of the contract there was also designed a planar cryogenic target, which was equipped with a “sliced” metal plate connected with a Dewar-type tubing for a liquid nitrogen flow. The construction enabled the target plate to be positioned on the z-axis, at a chosen distance from the PF electrode outlet. In order to make possible the formation of a heavy-ice (D_2O) layer upon the target plate there was installed an additional vacuum valve, which supplied a heavy-water vapor. A general view of the planar cryogenic target has been shown in Fig. 2.

To produce gas-puffed targets, the inner electrode of the PF-360 machine was modified. It was equipped with a new front plate with a dozen of narrow nozzles with axes titled slightly to the z-axis, because such a constructionappeared to be

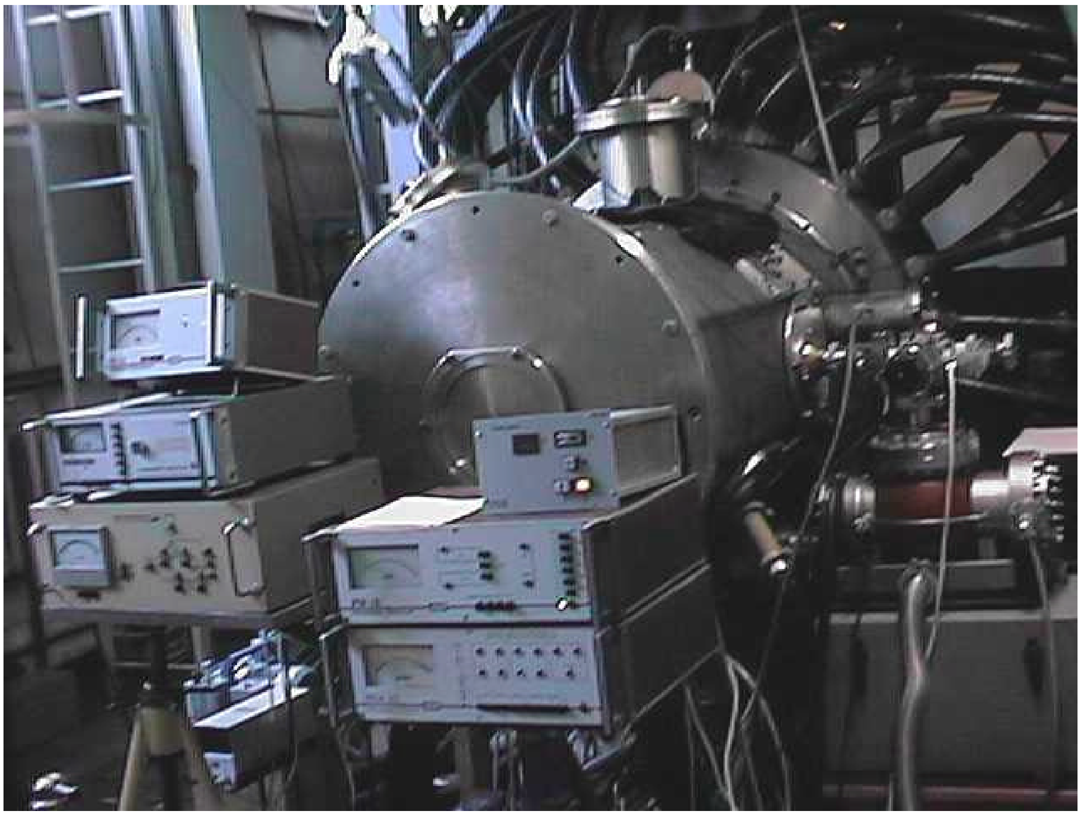


Fig. 1. A general view of the modernized PF-360 machine. Around the main experimental chamber there are visible measuring tools designed for diagnostics of working gas conditions, X-rays, and fusion-produced neutrons. Additional silver-activation counters and scintillator-photomultiplier sets are situated outside the frame.

Fig. 2. A general view of the planar cryogenic target, which can be placed at a chosen distance from the PF electrode outlet. When liquid nitrogen is pumped through the inner tubes, and a small amount of heavy water (D_2O) is injected into the experimental chamber with an auxiliary valve, the target plate can be covered with a heavy-ice layer. To reduce the consumption of D_2O there is installed an external thermal shield.

more effective for the formation of localized gas-puffed targets [11]. A new fast-acting gas valve was designed and manufactured. It was activated with a current pulse supplied to the internal driving coil. The induced electromagnetic force moved the valve piston in the axial direction and it opened a ring-shaped gas plenum. After that the pressurized deuterium gas could flow through the nozzles into the current-sheath collapse region. Return motion of the valve piston was performed with a pneumatic pusher. A general view of the described gas valve has been shown in Fig. 3.

4. The second phase of the contract

During the second phase of the contract realization the complete assembling of the modernized PF-360 current-pulse generator was performed and the full experimental tests were carried out. Although during those tests several charging resistors became broken, the technical tests proved that the whole PF-360 machine can be operated up to 30 kV successfully. The current- and voltage-measuring experiment was also tested. It was proved that the modified PF-360 current-pulse generator, operated at U_0 = 30 kV with the normal load (i.e. with the experimental chamber filled up with deuterium under the pressure p_o = 6-8 mbar) can supply the peak current equal to about 1.8 MA. An example of typical current- and voltage-waveforms has been presented in Fig. 4.

At the same time there were performed exploitation tests of the planar cryogenic target placed within an auxiliary vacuum stand. It was demonstrated that a thickness the heavy-ice layer upon that target could be varied by a change in an amount of the injected heavy-water vapor, and by adjusting of a cooling rate (determined by a liquid nitrogen flow within the cooling circuit).

In order to make us of accelerated deuterons moving in the radial direction during the current-sheath collapse and the PF-pinch phase, there was proposed another version of the cryogenic target. It was designed as a thin-wall copper -tube of about 5 mm in diameter, and 150 mm in length. That needle-like cryogenic target was cooled down by an inside flow of a liquid nitrogen stream, and it was also covered with a thin heavy-ice layer. After the manufacturing the needle-type cryogenic target was also tested within the auxiliary volume stand. A general view of the needle target has been shown in Fig.5.

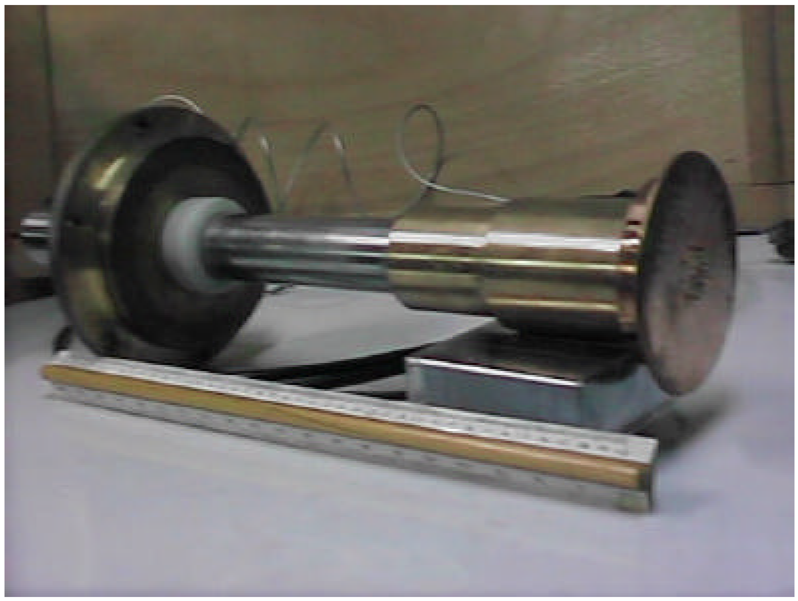


Fig. 3. A general view of the fast-acting gas valve, which was installed inside the inner electrode of the PF-360 machine. When the electromagnetic drive is powered from an auxiliary current-pulse generator, a ring-shaped piston opens a gas plenum and the working gas can flow out through nozzles in the front plate. Return motion of the piston is provided by a pneumatic drive supplied from a pressurized-air system.

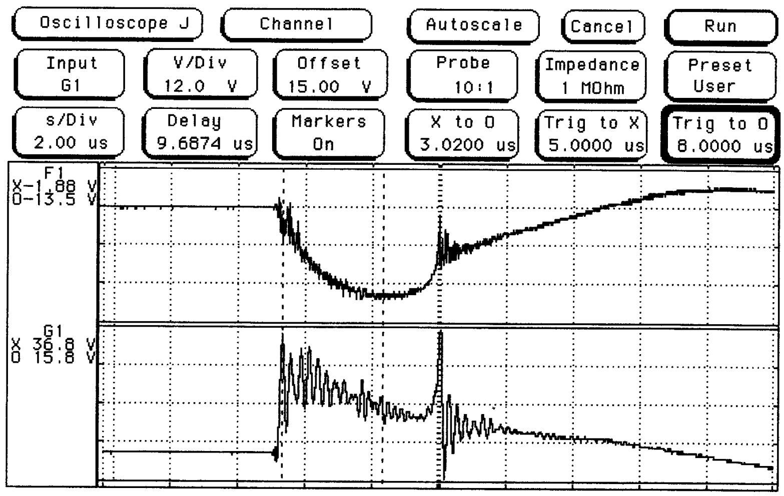


Fig. 4. Typical current- and voltage-traces, as registered for a single shot performed within the PF-360 machine. The discharge current was measured with a Rogowski coil placed inside the main current-collector, and the inter-electrode voltage was measured by means of a HV divider connected with the collector plates. During the current peculiarity, corresponding to the radial collapse of the current-sheath there is observed a distinct over-voltage pulse.

Fig. 5. A general view of the needle-type cryogenic target, which was placed at different distances from the PF electrode outlet. When liquid nitrogen was pumped through the inner tubes, and a small amount of heavy water (D_2O) was injected into the experimental chamber with an auxiliary valve, the target surface was covered with a heavy-ice layer. To reduce the consumption of D_2O a part of the Dewar tube was protected with a thermal shield.

To produce deuterium gas-puffed targets in the PF-360 chamber, the fast-acting gas valve (described in the previous section) was installed within the modified inner electrode. After the assembling of all auxiliary units (including a working gas supply unit, a pressurized-air system for the pneumatic return-drive, an auxiliary current-pulse generator for the electromagnetic drive), there were performed the full operational tests. As a result an amount of injected gas was determined as a function of electrical energy supplied to the investigated valve. It enabled gaseous conditions to be adjusted by a change of the supply voltage value (at the constant capacity of the additional current-pulse generator).

During the second phase of the contract there were also performed optimization studies of the PF-360 machine equipped with the planar cryogenic target described above. That target was placed at different distances from the electrode outlet, as shown in Fig. 6.

After the formation of the heavy-ice layers there were carried out measurements of discharge voltage- and current-waveforms, X-rays, and fusion-produced neutrons. A comparison of the volume and current-traces showed that the positioning of the planar cryogenic target did not influence PF discharges considerably, provided that it was placed not too close to the electrode outlet (i.e. at a distance $L_o > 80$ mm).

The X-ray measurements were carried out by means of X-ray pinhole camera and VAJ-type radiometers. The X-ray pinhole pictures, which were taken side-on the electrode outlet, showed that the X-ray emission from the PF pinch column did not change considerably when the planar cryogenic target was placed at different axial positions. Some examples of the X-ray pinhole pictures have been presented in Fig. 7.

The most important results were the neutron yield measurements, which were performed at various initial deuterium pressures (varied from 6.0 mbar to 12 mbar D_2), and at different positions of the planar cryogenic target. Simultaneously with time-integrated measurements there were performed time-resolved studies. Examples of typical time-resolved neutron signals have been presented in Fig. 8.

The neutron yields were averaged over the series of successive PF shots performed under identical experimental conditions. The experimental results, which were obtained at $U_o = 30$ kV, $W_o = 130$ kJ, have been compared in Fig. 9.

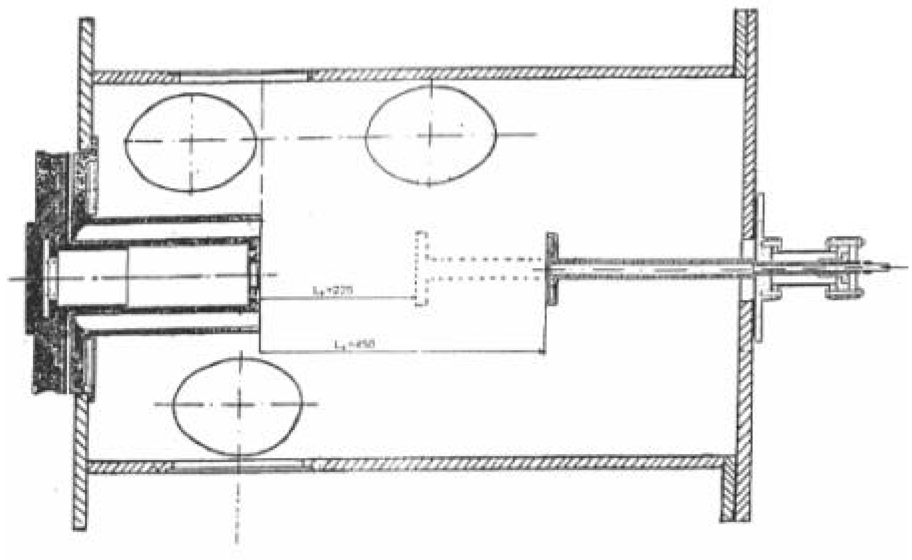
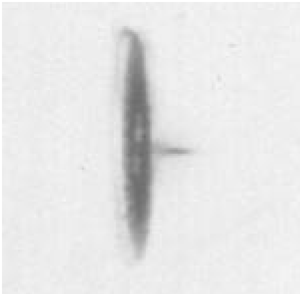


Fig. 6. Positioning of the planar cryogenic target inside the main vacuum chamber of the PF-360 machine, as realized during the neutron yield optimization experiments.

p_0 = 10 mbar, l_o = 450 mm,
$Y_n = 0.95 \times 10^{10}$

p_0 = 8.0 mbar, l_o = 110 mm,
$Y_n = 2.47 \times 10^{10}$



p_0 = 8.0 mbar, l_o = 110 mm,
$Y_n = 1.88 \times 10^{10}$

Fig. 7. Soft X-ray pinhole pictures, which were taken with a pinhole camera, for several discharges performed in the PF-360 machine equipped with the planar cryogenic target. It can easily be seen that the placement of the planar cryogenic target did not influence the X-ray emitting plasma region noticeably.

p_0 = 10.3 mbar
l_o = 230 mm
$Y_n = 2.7 \times 10^{10}$

p_0 = 8.3 mbar
l_o = 225 mm
$Y_n = 2.9 \times 10^{10}$

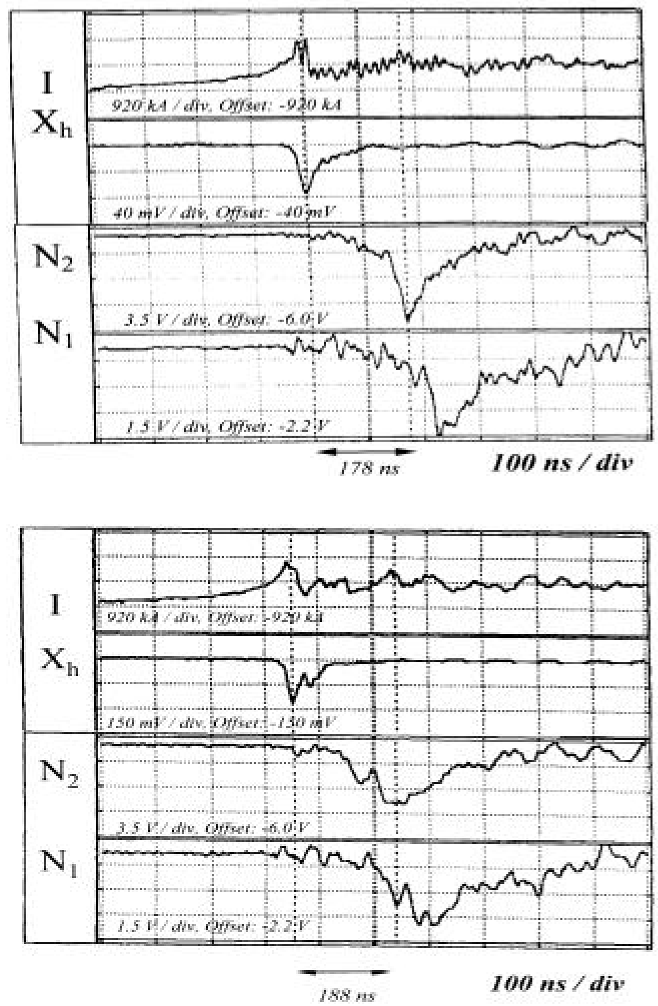


Fig. 8. Typical time-resolved traces from the scintillator-photomultiplier sets, which were taken for PF shots with the planar cryogenic target at W_0 = 130 kJ. For a comparison there are also shown the discharge current (I), and hard X-rays (X_h) waveforms.

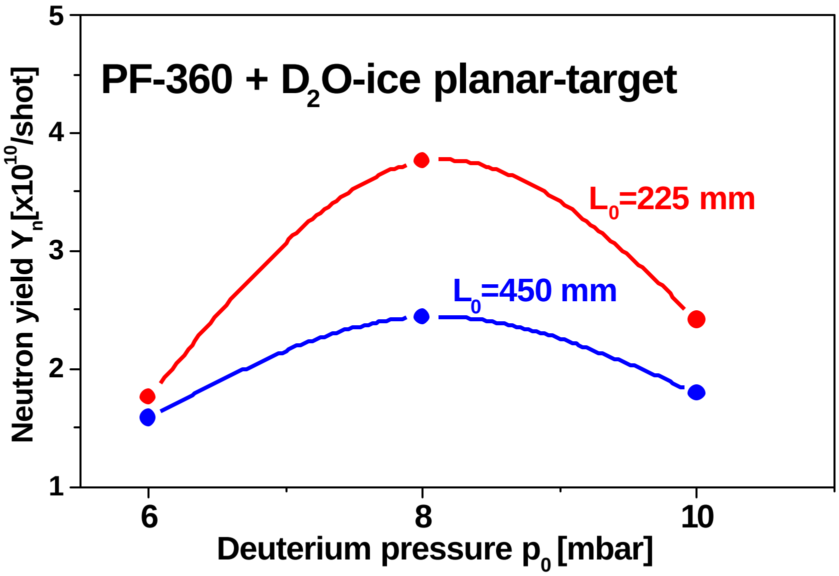


Fig. 9. Average neutron yields as a function of the initial deuterium pressure, as measured for PF experiments with the planar cryogenic target. Several series of PF shots were performed at U_0 = 30 kV, W_0 = 130 kJ, and different axial positions of the investigated target. The best results were achieved when the target (covered with a heavy-ice layer) was placed at a distance of L_0 = 225 mm from the electrode outlet.

It was found that the application of the planar cryogenic target, covered with heavy-ice layers of the controlled thickness, caused a considerable increase in an average neutron yield (Y_n). When such a target was placed at an optimized distance L_0 = 225 mm from the electrode outlet, it was possible to rise Y_n from 2.4 x 10^{10} to about 3.8 x 10^{10} neutrons/shot.

5. The third phase of the contract

During the third phase particular attention was paid to the neutron optimization experiments with the use of a needle-type cryogenic targets and deuterium gas-puffed targets. Modeling of ion trajectories within the collapsing current-sheath and the PF pinch column, which were performed with taking into account the appearance of current filaments [12-13], showed that a considerable portion of accelerated deuterons (during their gyro-motion) move in the radial direction. Therefore, it was reasonable to use those deuterons in order to increase a number of D-D fusion reactions by the application of the needle-type cryogenic target, as described in the previous section. That needle-type target was placed on the z-axis, at different distances from the electrode outlet, as shown in Fig. 10.

Several series of the PF experiments were carried out with simultaneous measurements of X-ray and neutron emissions. The X-ray measurements, as performed with the X-ray pinhole camera placed side-on the main experimental chamber, showed that the application of the needle cryogenic target did not influence the X-ray emitted region considerably, when the target was placed not too close to the electrode outlet (at L_0 > 20 mm). Some examples of the soft X-ray pinhole pictures, as taken for the shots with the needle cryogenic target, have been shown in Fig. 11.

The neutron yield measurements showed that the placement of the needle cryogenic target near the PF-360 electrode outlet (at L_o = 20 mm) did not influence the average neutron emission. It was, however, observed that with the positioning of that target at larger distances (at L_o = 65-100 mm) one could achieve an increase in the neutron yield, particularly at higher operational pressures. The neutron data from the described PF experiments have been presented in Fig. 12.

It was found experimentally that the highest neutron yield (Y_n= 2.3 x 10^{10} neutrons/shot) from PF discharges performed with the needle-type cryogenic target (which was covered with the heavy-ice layer) was obtained at the initial deuterium pressure p_o = 10 mbar D_2.

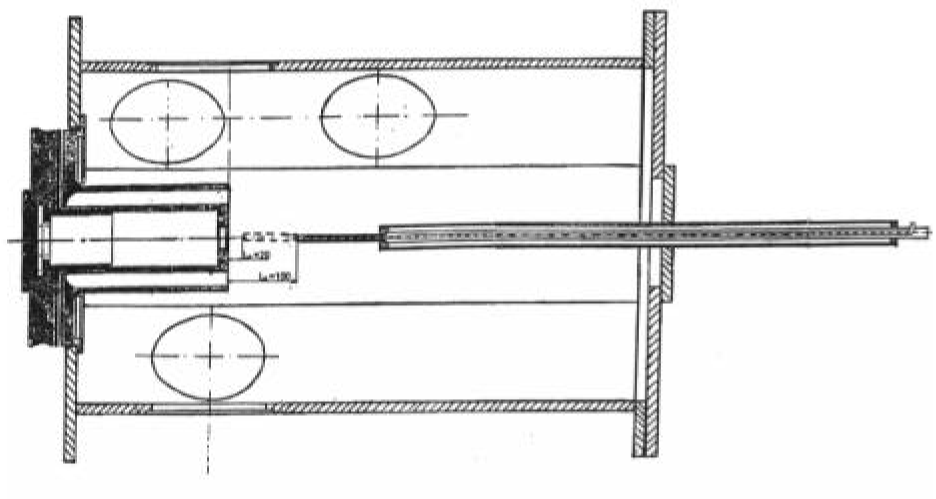
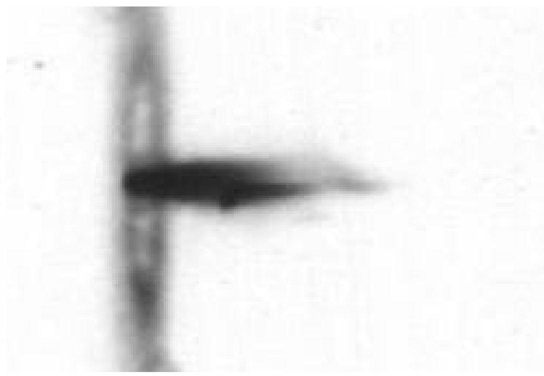


Fig. 10. Positioning of the needle cryogenic target inside the main vacuum chamber of the PF-360 machine, as realized during the neutron yield optimization experiments.

p_0 = 5.9 mbar, l_o = 65 mm,
Y_n = 0.7 x 10^{10}

p_0 = 8.1 mbar, l_o = 20 mm,
Y_n = 2.2 x 10^{10}



p_0 = 8..1 mbar, l_o = 100 mm,
Y_n = 0.7 x 10^{10}

p_0 = 8.1 mbar, l_o = 20 mm,
Y_n = 3.3 x 10^{10}

Fig. 11. Examples of soft X-ray pinhole pictures, as taken with a pinhole camera, for several discharges performed with the PF-360 machine equipped with the needle cryogenic target. It can be seen that the target was slightly off the pinch axis, but its application did not change the X-ray emitting region considerably.

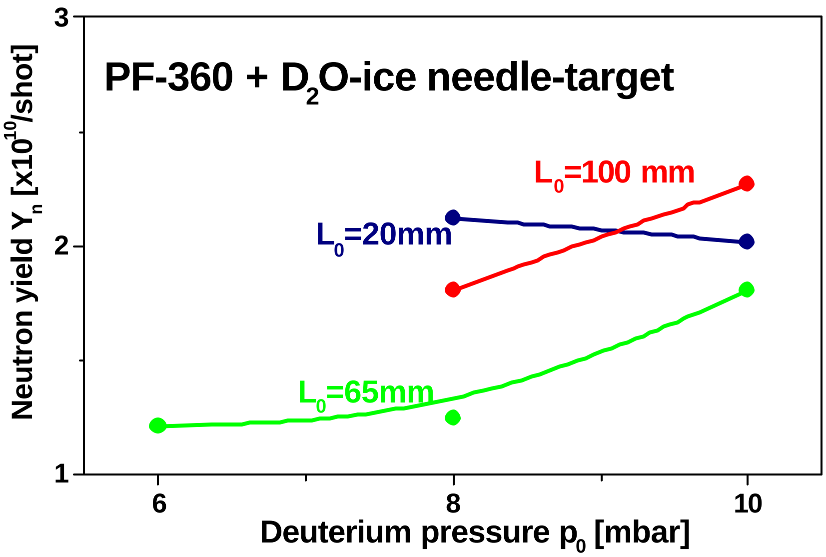


Fig. 12. Average neutron yields as a function of the initial deuterium pressure, as measured for PF experiments with the needle cryogenic target. Several series of PF shots were performed at U_0 = 30 kV, W_0 = 130 kJ, for different positions of the needle target. The highest neutron yield was achieved at higher initial pressures (p_0 = 10 mbar D_2), when the target top was placed at a relatively large distance (L_0 = 100 mm) from the electrode outlet.

Particular attention was also paid to PF experiments with deuterium-gas puffed targets. The fast acting gas valve, as described in the previous section, was operated mainly at V_v = 5 cm^3, p_v = 21 bar D_2, U_v = 3.2-3.5 kV. During the PF experiments performed that gas valve was activated 400 µs or 500 µs before triggering of the main PF discharge. Several series of PF shots were performed at various initial pressures in the experimental chamber, which were varied from about 5.3 mbar D_2 to about 8.0 mbar D_2. The X-ray measurements, which were carried out with the X-ray pinhole camera, showed noticeable differences in the X-ray emission, depending on the initial gas conditions and the gas-puffed target formation. Some examples of the X-ray pinhole pictures have been shown in Fig. 13.

The neutron measurements from PF shots, which were performed with deuterium-puffed targets, showed that an average neutron yield depends also strongly on the gas conditions. The neutron emission data have been compiled in Fig. 14.

It was found that for the deuterium-puffed PF discharges the highest neutron yield, equal to $Y_n = 2.5 \times 10^{10}$ neutrons/shot, was obtained at the initial pressure p_o = 5.95 mbar D_2 and at a lower density of the deuterium target (obtained at U_v = 3.2 kV).

6. Summary and conclusions

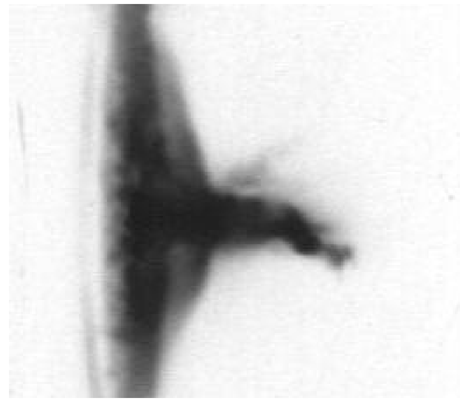
The main objectives of the reported contract were achieved within three phases, as described in the interim reports [6-7] and previous sections of this report.

- The PF-360 machine was modified, and in particular the PF-360 current-pulse generator was modernized in order to enable several series of the optimization experiments to be performed. Also installed was a new set of the larger electrodes of 300 mm in length, 120 mm and 170 in diameter, respectively. The inner electrode was modified to make possible the installation of the fast-acting gas valve. That electrode was equipped with a front plate, in which narrow nozzles were drilled. To enable the formation of gas-puffed targets within the PF pinch region.

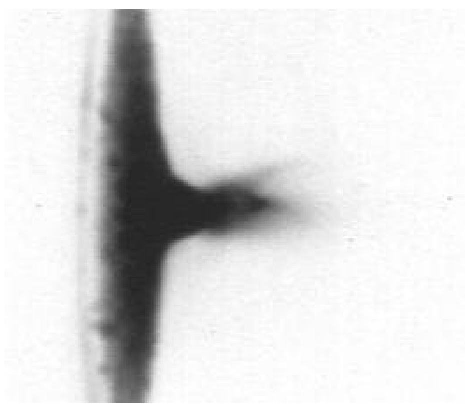
- To make possible detailed measurements of the neutron yield from PF shots additional measuring equipment was completed. Initially there were installed

p_0 = 5.6 mbar, Y_n = 3.8 x 10^{10}

p_0 = 5.7 mbar, Y_n = 0.6 x 10^{10}



p_0 = 5.2 mbar, Y_n = 6.0 x 10^{10}



p_0 = 5.4 mbar, Y_n = 1.5 x 10^{10}

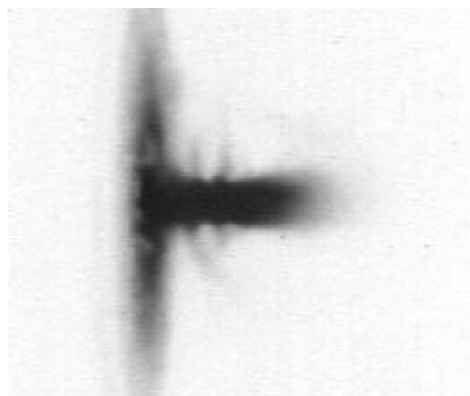


Fig. 13. Soft X-ray pinhole pictures, which were taken with a pinhole camera for several discharges performed in the PF-360 machine equipped with the gas-puffing equipment. One can observe noticeable differences in the X-ray emission region, which depend on the gas pressure and the formation of gas-puffed targets.

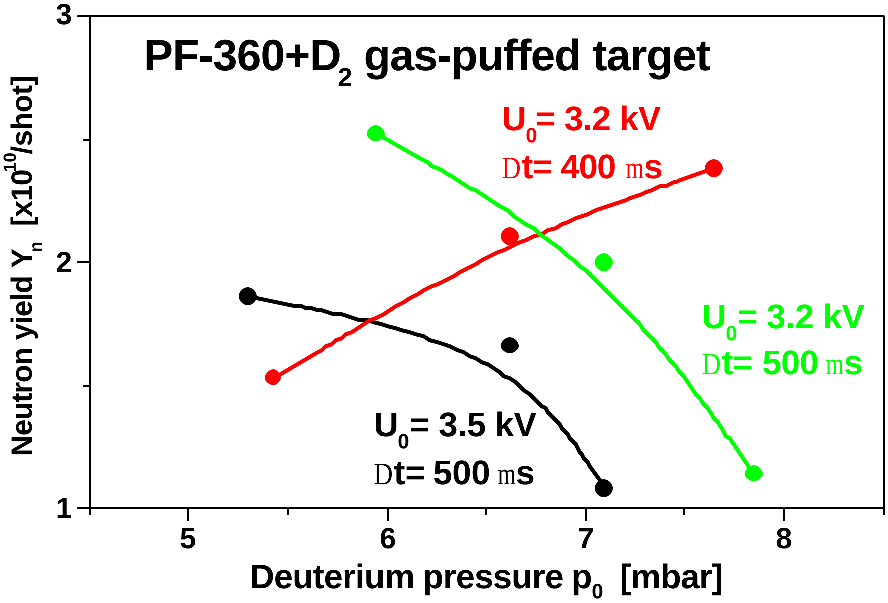


Fig. 14. Average neutron yields versus the initial deuterium pressure, as measured for the PF experiments performed with additional gas-puffed targets.

two silver activation counters and two new scintillator-photomultiplier sets. During the final phase of the contract there were also installed 5 new activation counters, which were placed at different angles to the z-axis of the PF-360 machine, to make possible routine measurements of a neutron emission anisotropy.

- To make use of accelerated primary deuterons, which usually escape from the PF pinch region, there were designed and manufactured two different cryogenic targets covered with heavy-ice (D_2O) layers of the controlled thickness. The planar cryogenic target was placed in front of the electrode outlet. The needle cryogenic target was located on the z-axis, in the PF-pinch region.

- The detailed neutron measurements, which were performed without and with the planar cryogenic target, showed that a considerable increase in the average neutron Y_n could be achieved. Under the determined experimental conditions (U_o = 30 kV, W_o = 180 kJ, p_o = 8 mbar D_2, and a distance between the electrode outlet and the target plate L_0 = 225 mm) Y_n was raised from 2.4 x 10^{10} to about 3.8 x 10^{10} neutrons/shot.

- Comparative neutron measurements, which were carried out with the use of the needle cryogenic target, showed that the average neutron yield could also be increased noticeably. Under the determined operating conditions (U_2 = 30 kV, W_o = 130 kJ, p_o = 8 mbar D_2 , and the distance between the front electrode plate and the needle target L_o = 20 mm) Y_n was raised from 1.2 x 10^{10} to about 2.2 x 10^{10} neutrons/shot. The highest neutron yield from PF shots with the needle cryogenic was, however, observed at higher initial filling pressure (i.e. at p_o 10 mbar D_2).

- In order to influence dynamics of current sheath motion during the PF radial-collapse phase there was designed and applied the fast acting gas-valve and the appropriate auxiliary equipment (supply units). Several series of PF experiment, as performed with deuterium-puffed targets, demonstrated that one can operate the PF machine at a lower initial filling pressure (p_o = 5.95 mbar D_2). When the gas valve operation was optimized (U_v = 3.2 kV, the valve activation Δt = 400 µs before the main discharge initiation), a relatively high average yield (Y_n = 2.5 x 10^{10} neutrons/shot) was obtained.

- The highest neutron yields from 130-kJ PF shots (Y_n =3.8 x 10^{10} neutrons/shot) have been so far achieved with the use of the D_2O-ice planar targets. The neutron anisotropy was about A = 30% and it did not changed considerably, although the use of beam-target interaction could of course influence the anisotropy value under given experimental conditions.

A comparative analysis of all the experimental data showed that it is possible to increase a neutron yield by the application of the techniques based on the use of additional heavy-ice targets and/or deuterium gas-puffed targets. In the first case an average neutron yield is increased by beam-target interactions. The directed beams of accelerated primary deuterons, which usually escape from the PF pinch column, contain a large number of fast deuterons, e.g. a moderate energy (about 70 kJ) PF-shot can emit 10^{15} deuterons of energy above 300 keV mainly in the downstream direction [14]. Such energetic deuterons can evidently be used for the production of fast neutrons from D-D reactions within solid-state targets containing deuterium (e.g. heavy-ice layers).

The higher neutron yields obtained with the D_2O-ice planar targets can be explained by the fact that the population of fast deuterons moving in the axial direction is higher than that of deuterons moving in the radial direction. Also the D_2O-ice needle target, placed on the PF pinch axis, disturbs the formation of the PF pinch column stronger than the planar cryogenic target, placed at a larger distance from the electrode outlet.

In the case of deuterium gas-puffed targets the situation is more complicated, because the interaction of the current-sheath layer with a deuterium cloud depends on many parameters and it involves different mechanisms, including also the generation of various instabilities. The optimization of PF gas-puffed facilities could, however, identify the best experimental conditions, as described above.

In summary one can formulate the conclusions, as follows:

- The both developed techniques can be used for the optimization of neutron yields from PF machines.

- The described techniques should be implemented in larger PF facilities, in order to verify the previous statements and to determine the optimal experimental conditions.

- The technique involving cryogenic targets could still be optimized by the application of targets containing more deuterium (e.g. pure frozen deuterium), although it would require more sophisticated and expensive cryogenic experiment.

- Also the technique involving deuterium-puffed targets could be improved by the optimization of nozzles and gas conditions, e.g. by the variation of a gas plenum capacity and pressure.

According to the F61775-99-WE088 contract requirements, the most important results of the above studies were presented at the IEEE International Conference on Plasma Science (ICOPS-2000), which was held in New Orleans, Louisiana, on June 4-7, 2000 [15]. Those results were discussed with a group of US experts representing the Air Force Research Laboratory in Albuquerque, the Nuclear Experiments Department of the Texas A&M University, and the Defense Threat Reduction Agency in Washington, DC. The recent results, which were obtained during the final phase of the contract realization, are to be presented at international conferences in Alushta Ukraine [16-17] and in Quebec, Canada [18], provided that there is no objection from our partners and supervisers.

The implementation of the developed techniques in the PF-1000 machine could be performed by joint teams of the Soltan Institute for Nuclear Studies (IPJ) and Institute of Plasma Physics and Technology (IFPiLM) in the near future, provided that appropriate funds for manpower and materials are available.

Any further development of solid-state targets as well as gas-puffed ones could also be performed in about one year, if new funds are granted. Both teams mentioned above are able to prepare new proposals upon request.

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17. J. Zebrowski, J. Baranowski, L. Jakubowski, M.J. Sadowski, and J. Stanislawski; Study of fusion neutron yield from PF-360 facility equipped with solid-state or gas-puffed targets – a paper to be presented at XIII Ukrainian Conf. & School on Plasma Phys. & Controlled Fusion (Alushta, Ukraine, Sept. 11-16, 2000).
18. M.J. Sadowski, and M. Scholz; The main issues of dense magnetized plasma studies in Poland – a paper to be presented at 2000 International Congress on Plasma Physics & 42nd Annual Meeting of DPP, American Physical Society (Quebec City, Canada, October 23-27, 2000).

Appendix 1

Abstract of the paper presented at the IEEE International Conference on Plasma Science ICOPS-2000 (New Orleans, Lu, June 4-7, 2000).

ICOPS 2000

IEEE Conference Record – Abstracts

The 27th IEEE International Conference on Plasma Science

IEEE

New Orleans, Louisiana, USA
June 4 – 7, 2000

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NEW PLASMA-FOCUS EXPERIMENTS WITHOUT AND WITH ADDITIONAL TARGETS

M.Sadowski[1], P.Kubes[3], J.Kravarik[3], M.Paduch[2], E.Skladnik[1], M.Scholz[2], K.Tomaszewski[2] and J. Zebrowski[1]

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[2] Inst. of Plasma Phys. & Laser Microfusion, 00-908 Warsaw, Poland
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The paper reports on results of recent Plasma-Focus (PF) experiments performed with medium-scale machines operated at 60-180 kJ. The first series of PF discharges was carried out within PF-150 machine [1] at 60 kJ, 28 kV. The device was equipped with Mather-type electrodes of 100 mm and 50 mm in diameter, and 200 mm in length. Attention was paid to current-sheath (CS) and PF pinch dynamics, which was investigated with high-speed framing camera [1], consisted of two VR channels and two soft X-ray modules. Exposition of VR frames was about 1 ns, and that of X-ray frames was about 0.8 ns. Synchronization was realized with fast photo-diodes registering the CS radiation. Electrical signals were stored with TDS784A digital oscilloscope, and all the frames were elaborated with image capturing and processing system (AICPS). Measurements were also performed with X-ray pinhole cameras and neutron counters. Comparison of the VR pictures and corresponding X-ray images revealed correlation between fine structures formed inside the pinch column.

The second series of experiments within PF-150 machine was carried out with solid targets made of thin metal- or carbon-wires, fixed on the z-axis at the electrode outlet. Using the same diagnostic equipment, it was observed that the interaction of the low-mass CS layer with the wire target produces an almost homogenous plasma column, which does not expand considerably during the CS collapse process. At the same time the X-ray emission along the z-axis is considerably higher that that emitted in the radial directions.

The third series of PF experiments was performed within PF-360 machine [2] equipped with the Mather-type electrodes of 170 mm and 120 mm in diameter, and 300 mm in length. The system was operated at 110 kJ, 30 kV, or 176 kJ, 35 kV. Several additional diagnostic techniques were applied to study time-integrated and time-resolved characteristics of the charged particle emissions. To increase a neutron yield from fusion reactions the use was made of cryogenic targets in the form of heavy-ice (D_2O) layers deposited upon special cryogenic targets. Considerable differences in the neutron yield have been observed in dependence on the experimental conditions applied. These new experiments are described, and the results are compared with those of previous PF studies [3].

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Bayou II and IV • 10:00 a.m. • Monday, June 5, 2000

ORAL SESSION 1D
SLOW WAVE DEVICES

Chair: **David Whaley**
Northrop Gruman Corporation

Appendix 2

Abstract of the invited talk to be given at the XIII Ukrainian Conference & School on Plasma Physics & Controlled Fusion (Alushta, Ukraine, Sept. 11-16, 2000).

PROGRESS IN DENSE MAGNETIZED PLASMA RESEARCH IN POLAND; A REVIEW

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This invited talk describes recent dense magnetized plasma (DMP) experiments carried out with different Plasma-Focus (PF) facilities in Poland, investigated at energy ranging from 40 kJ to about 800 kJ. The first series of PF shots was performed with PF-150 device operated at IFPiLM in Warsaw. That device was equipped with Mather-type electrodes of 100 mm and 50 mm in diameter, and 200 mm in length, powered at 41 kJ / 28 kV. To investigate dynamics of VR and X-ray emission the use was made of a multi-frame imaging system consisted of two VR measuring channels (DUPLO high-speed camera) and two separate X-ray framing modules. The VR and X-ray frames were synchronized in pairs, and their exposition times were about 1 ns. The synchronization with PF discharges was realized by means of fast photo-diodes, which observed current-sheath (CS) motion. All electrical signals were stored with TDS784A digital oscilloscope, and frames were elaborated with an automatic image capturing and processing system (AICPS). The VR pictures and corresponding X-ray images demonstrated correlation of fine structures formed within the pinch column.

Another series of experiments with PF-150 device was devoted to studies of solid targets made of thin metal or carbon fibers, which were placed on the z-axis at the electrode outlet. Using the diagnostic equipment described above it was proved that the interaction of the low-mass CS layer with the fiber target produces almost uniform corona plasma, which is relatively stable during the whole CS collapse phase. Simultaneously, using an XUV spectrometer, a Czech team from CVUT in Prague registered various spectral lines belonging to OV-OVII and CV-CVI ions, as well as high-intensity continuum. The H-like carbon lines as well as He-like resonance lines have been observed with the carbon fiber only.

The third series of PF experiments was carried out with PF-360 facility operated at IPJ in Swierk. That facility was equipped with Mather-type electrodes of 170 mm and 120 mm in diameter, and 300 mm in length. They were powered at 122 kJ / 30 kV or 166 kJ / 35 kV. Different diagnostic techniques were applied to study time-integrated and time-resolved characteristics of charged particles and neutron pulses. In order to increase a neutron yield there were used targets made of heavy ice (D_2O) layers deposited upon special (planar or needle-like) cryogenic devices, which were placed in front of the electrode outlet. In some PF discharges there were also applied additional gaseous targets in the pinch region, which were produced with a fast-acting gas valve located inside the inner electrode. Considerable increase in the neutron yield has been achieved at determined experimental conditions.

Several series of PF experiments were performed by a joint team from IFPiLM and IPJ with the largest (megajoule) PF-1000 facility, which is operated at IFPiLM in Warsaw. That facility has been equipped with new large Mather-type electrodes of 400 mm and 231 mm in diameter, and 600 mm in length. The recent experiments have been carried out at energy levels from 500 kJ to about 800 kJ. Dynamics of a CS layer was studied with high-speed cameras, and from smear VR pictures an average velocity of the radial compression has been determined. Using an X-ray pinhole camera there was studied the formation of “hot-spots” within the pinch column. Also studied were fast (> 80 keV) ion beams emitted along the z-axis. The ion images registered with SSNTDs confirmed the emission of bunches of fast ion beams. Research on the neutron yield optimization has just been started. In conclusions this invited talk describes also aims and prospects of DMP research program in Poland, which is realized in collaboration of IFPiLM and IPJ with some foreign centers.

Appendix 3

Abstract of the paper to be presented at the XIII Ukrainian Conference & School on Plasma Physics & Controlled Fusion (Alushta, Ukraine, Sept. 11-16, 2000).

STUDY OF FUSION NEUTRON YIELD FROM PF-360 FACILITY EQUIPPED WITH SOLID-STATE OR GAS-PUFFED TARGETS

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The paper reports on results of Plasma-Focus (PF) investigations carried out within the PF-360 device, which was equipped with exchangeable targets made of heavy-ice (D_2O) layers or D_2-gas puffs. The main aim of these studies was to increase a neutron yield from PF discharges by using fast deuteron beams, which are usually emitted from a pinch column and which can interact with additional targets.

The PF-360 facility was equipped with coaxial Mather-type electrodes of 170 mm and 120 mm in diameter, respectively. The both electrodes were about 300 mm in length, but the inner electrode (anode) was embraced with a ceramic insulator tubing of 80 mm in length. An initial filling pressure in the main experimental chamber was varied from about 6.0 to 12 mbar D_2, and in some comparative shots there was applied a small Ar-gas admixture. The PF discharges were powered from a 288-μF condenser bank, which was charged up to 110 kJ at 30 kV or 176 kJ at 35 kV.

Several diagnostic techniques were applied simultaneously. Neutron yields were measured with two silver-activation counters and two scintillation detectors. X-ray emission studies were carried out by means of X-ray pinhole cameras and VAJ-type radiometers. Since the previous studies of ion emissions from the PF-360 device, which were performed with nuclear track detectors (NTDs) and filtered scintillator sets, proved that many fast (> 80 keV) deuterons escape from a PF pinch column, it was decided to apply additional targets with deuterium for D-D reactions.

In order to use the pulsed deuteron beams emitted along the z-axis, there was designed a "planar" cryogenic target in the form of a "sliced" metal plate equipped with a channel for a continuos flow of liquid nitrogen. That target could be placed at various axial positions. When a small amount of heavy-water (D_2O) was injected into the main experimental chamber (through an auxiliary vacuum valve) the target surface was covered with a thin heavy-ice layer. The thickness of this layer was varied by a change in an amount of injected heavy water and cooling medium flow. Several series of PF shots were performed with the planar target placed at different distances from the electrode outlet. Preliminary optimization measurements have demonstrated a considerable increase in the average neutron yield (from 2.4 x 10^{10} to about 3.8 x 10^{10}) under the determined experimental conditions (p_0 = 8 mbar D_2, U_0 = 30 kV, W_0 = 130 kJ, and the target at a distance l_0 = 225 mm from the electrode ends).

To make use of accelerated deuterons moving in the radial direction during the current-sheath collapse phase, there was designed another version of the cryogenic target. It had a "needle-like" form of 5 mm in diameter, and it could be adjusted along the pinch column axis. Preliminary optimization measurements have shown that an increase in the average neutron yield (up to about 2.5 x 10^{10}) can be achieved, but such a "needle-like" target disturbed the pinch column too much.

Another series of PF experiments have been carried out with the use of a special fast-acting gas valve, which was situated behind the front plate of the inner electrode. That valve was powered before the current-sheath collapse, and it produced a D_2-gas target in the pinch region. Preliminary tests, as performed with the D_2-puffing under different experimental conditions, have shown that the gas-puffed target can change dynamics of the PF compression phase, but under appropriate gas conditions an average neutron yield can also be increased considerably.

Appendix 4

Abstract of the paper to be presented at 2000 International Congress on Plasma Physics & 42^{nd} Annual Meeting of DPP, American Physical Society (Quebec City, Canada, October 23-27, 2000).

Abstract for DPP-APS

THE MAIN ISSUES OF DENSE MAGNETIZED PLASMA STUDIES IN POLAND

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The paper describes recent DMP experiments carried out with different Plasma-Focus (PF) facilities in Poland, at energy from 40 kJ to 800 kJ. Some experiments were performed with PF-150 device powered at 41 kJ / 28 kV. The use was made of a multi-frame imaging system. The VR pictures and corresponding X-ray images demonstrated correlation of fine structures formed within the pinch column. Other experiments were performed with metal or carbon fibers. It was proved that the interaction of the CS layer produces almost uniform corona plasma, which is relatively stable during the whole collapse phase. There were registered various spectral lines and intense continuum.

Numerous PF experiments were carried out with PF-360 facility powered at 122-166 kJ / 30-35 kV. Different diagnostics were applied to study charged particles and neutron pulses. There were used special cryogenic targets or gaseous targets. A considerable increase in the neutron yield has been achieved at determined experimental conditions.

Several series of experiments were performed with PF-1000 facility equipped with new large electrodes, and operated at 500-800 kJ. Dynamics of a CS layer was studied with high-speed cameras. Using an X-ray pinhole camera, there was studied the formation of “hot-spots”. Also studied were fast (> 80 keV) ion beams emitted along the z-axis. Research on the neutron yield optimization has also been performed. In conclusions there are described aims and prospects of DMP research program in Poland.